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ABSTRACT

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Presented here is a description of the process variables encountered in the Gas Tungsten Arc and the Gas Metal Arc Welding processes; the description emphasis is placed on the variable interdependence which occurs in these processes. From these variable relationships, a ninth order non-linear state variable description of the Gas Metal Arc process is developed using nine first order non-linear differential relations. Further definition of the exact nature of these relations will permit the development of a second generation automatic welder which will be a dramatic improvement over existing machines.

This work is believed to be the first attempt to apply modern control theory to welding.

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AUTOMATIC WELDING CONTROL USING A STATE VARIABLE MODEL

by

WILLIAM VINCENT MOODY

B.S. Ocean Engineering, U.S. Naval Academy
(1972)

Submitted in Partial Fulfillment
of the Requirements for the
Degree of

MASTER OF SCIENCE IN OCEAN ENGINEERING

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May 1979

AUTOMATIC WELDING CONTROL USING A STATE VARIABLE MODEL

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WILLIAM VINCENT MOODY

Submitted to the Department of Ocean Engineering and the Department of Mechanical Engineering on May 11, 1979, in partial fulfillment of the requirements for the Degree of Master of Science in Ocean Engineering and the Degree of Master of Science in Mechanical Engineering.

ABSTRACT

Although automatic welders have existed commercially for at least the past ten years, they have proved inadequate to fulfill the needs of current shipbuilding, marine structure and major pipeline manufacturing contractors. The recent Alaskan pipeline construction program where hundreds of skilled manual welding craftsmen were sought out and sent to our most northern state is a good example. The development of a reliable and adaptable automatic welding process capable of rapidly producing good weldments is considered to be a primary requirement of today's industry.

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Supervisor: Koichi Masubuchi
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Title: Professor of Mechanical Engineering

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I would like to express my appreciation to Professor Koichi Masubuchi and Professor Henry Paynter for the instruction, contributions and suggestions that I received both in the courses which they taught and in their support of this work. Without their guidance, this thesis would not have achieved its final form.

The real purpose of scientific method is to make sure Nature hasn't misled you into thinking you know something you don't actually know. . . . If you get careless or go romanticizing scientific information, giving it a flourish here and there, Nature will soon make a complete fool out of you.

--Robert M. Pirsig
Zen and the Art of Motorcycle Maintenance

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I. INTRODUCTION

The label "Automatic" has been attached to many different welding processes which have been developed by industry or discussed in technical literature over the last ten years; each of these automatic processes has attempted to reduce the decision making or manipulative functions played by the human welding operator by increasing the "intelligence" of the machine. However, the success of the above mentioned processes is dubious if the goal of automation is to develop a truely versatile, adaptable and dependable welding process. The automatic machines currently in operation have narrow and extremely specific ranges of application.

Two broad categories of automatic welders are employed in present industrial applications: "robot" welders and modified manual welders. Seemingly, each new issue of the popular welding journals contains at least one description of a new automatic machine which falls into one of the above categories. Automation systems of various stages of complexity have been designed and applied to welding processes such as Gas Metal Arc (GMA), Gas Tungsten Arc (GTA), Resistance, Electroslag and Submerged Arc. However, with the exception of certain assembly line type production processes such as the automobile industry, manual production welding completely dominates industry worldwide. One only has to look at current shipyard or pipeline production operations to verify this fact.

Successful automation of welding processes is attractive for one or more of the following reasons:

Economic Considerations

- Cheaper production costs
- Reduced on-site manpower requirements
- Reduced welder training costs
- Increased production rates

Weld Quality Improvement

- Provide near ideal welding conditions
- Weldment consistency and reproductiveness
- Immediate post-welding non-destructive testing
- Lower number of weld repairs

To realize these substantial advantages over manual welding, a second generation automatic machine must be developed.

Current automation systems employed on welders consist of some combination of open loop and closed loop control schemes. An open loop control scheme can be as simple as presetting the value of one process variable. The machine then attempts to match this preset value without any measured feedback. More advanced machines measure one or more of the variables in the welding process and, through the use of a controller, attempt to minimize variations of these variables from preset values. To illustrate the difference between an open loop and a closed loop control scheme, the variable <u>weld head (electrode) position</u> is a good example. In certain

pipeline manufacturing systems, the welding machine consists of multiple GMA welding heads which ride on a chain or steel band-type track that is attached circumferentially around the pipe. This is an open loop form of control because the track is preset and invariant; the success of this scheme depends on how carefully the operators prepare the joint and allign the track. Closed loop control of the <u>weld head (electrode) position</u> has been implemented on GMA machines designed to butt weld two flat plates. In this case, sensors such as a TV camera or a mechanical probe placed ahead of the electrode sense the track of the joint path and position the electrode via servomotor drives. By using feedback in this manner, joint irregularities can be overcome by the welding machine because the electrode tracking system can follow an imperfect joint matchup.

Current automatic welders are successful only under specific applications. The major problem with these current machines is that only selected process variables are monitored or controlled. Because there are a relatively large number of variables in any welding process, the relevance to the final weldment quality of the variables selected for control is critical. For the most part, the controlled variables in current machines include arc length, arc voltage or current, current pulsing, wire feed rate, electrode tracking path, and electrode traverse speed. Therefore, the successful

machine designer has been forced to choose the right combination of these variables to control in order to produce a successful machine.

Recent advances in control theory are predicated on the ability of the control engineer to successfully model a process so that all pertinent process variables can be identified and measured (or at least estimated); then the process variables are controlled by minimizing any variation about a desired set point. To date modern control theory has not been applied to welding processes for a variety of reasons; the primary hurdle thus far has been the inability to develop a successful model.

This work is the preliminary step of a multi-year project jointly headed by Professor Koichi Masubuchi, Professor Henry M. Paynter, and Mr. Frans Van Dyck at MIT to develop a fully automated, versatile and reliable welding process. This work will first identify a set of process variables taken from the Gas Metal Arc and Gas Tungsten Arc Welding processes. These processes were chosen because they appear to provide the broadest range of possible applications. Secondly, each variable will be discussed thoroughly with the emphasis placed on the variable's suitability in a feedback control system. Finally, problems such as measurement, estimation, and processing of each variable will be discussed.

The ultimate goal of this work is to provide the basis for a model of the GMA (or GTA) process and then to begin to "close the loop" in the control formulation. Once this first step is completed, the project will continue to develop a variable controlled welding process. This completed welding process, when coupled with immediate nondestructive weldment testing (NDT) and post-testing repair, will provide a rapid and reliable method for fabrication of such structures as U.S. Navy and commercial ships, pipeline systems, and large ocean platforms while incorporating the advantages listed earlier in this introduction.

II. WELDING PROCESS VARIABLES

Unlike many systems and processes that are controlled today, welding presents a major problem because the desired output is not measurable. The goal of any welding process is to produce a weldment that matches the base metal in chemical, metallurgical and mechanical properties. However, weldment qualities such as porosity, amount of fusion, hardness, toughness, tensil strength, etc., cannot be determined "on-line" while the welding operation is in progress. Only after the process is completed can a weldment sample be taken and tested for its qualities. Therefore, other properties of the welding system must be monitored and from these properties, projections and estimations of the weldment qualities can be made. These weldment quality projections are based upon empirical relationships that have been obtained from the millions of experiments completed by welding researchers.

Using this empirical data base, weldment quality can be controlled by measuring or estimating and then controlling a set of process variables. In the following discussion, this set of process variables will be broken up into two subsets: the control (or manipulative) variables and the state variables. The control (manipulative) variables are defined as those variables that can be manipulated directly by the welding machine or the welding operator. The state variables are defined as those variables which are determined by the welding process itself once the control (manipulative) variables have been set. The state variables cannot be manipulated directly but are functions of the welding process.

Figures 2-1 and 2-2 are block diagrams of the Gas Metal Arc and Gas Tungsten Arc welding processes. These diagrams identify the principal components of these systems. Through the use of these figures, the reader can gain an appreciation for the complexity of the welding processes and can identify how the following listing of state variables and control (manipulative) variables are related schematically. This list (Table 2-1) is meant to be as complete as possible and was developed from a similar list contained in Appendix C of reference 20.

TABLE 2-1

CONTROL AND STATE VARIABLES IN THE GMA AND GTA WELDING PROCESSES

Control (manipulative) Variables	State Variables
Current	Puddle Shape and Size (Penetration)
Voltage (AC or DC and polarity)	Metal Temperature Distribution
Pulsing Frequency and Shape	Arc Temperature
Traverse Speed	Arc Shape and Composition
Electrode Tracking Path	Arc Length
Welding Torch Movement	Metal Transfer Mode
Wire Feed Rate (GMA)	Arc Magnetic Field
Filler Wire Feed Rate (GTA)	Acoustic Emission
Composition and Flow Pattern of Protecting Gas	Radiant Light Emission
External Magnetic Fields Surrounding Arc	Electrode Extension Length (GMA)
Coolant Flow	

FIGURE 2-1

BLOCK DIAGRAM FOR MECHANIZED

GAS METAL ARC WELDING SYSTEMS

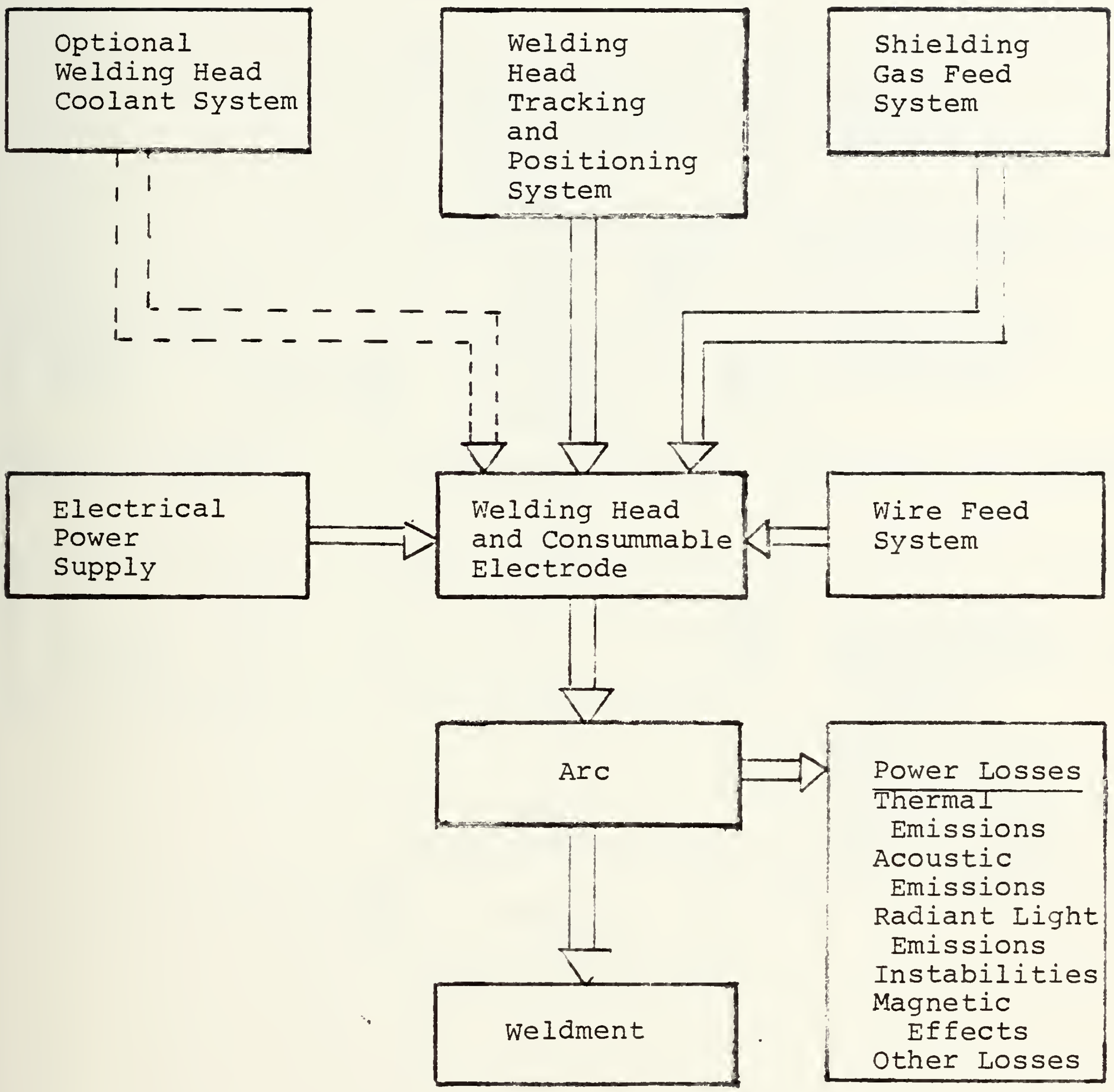
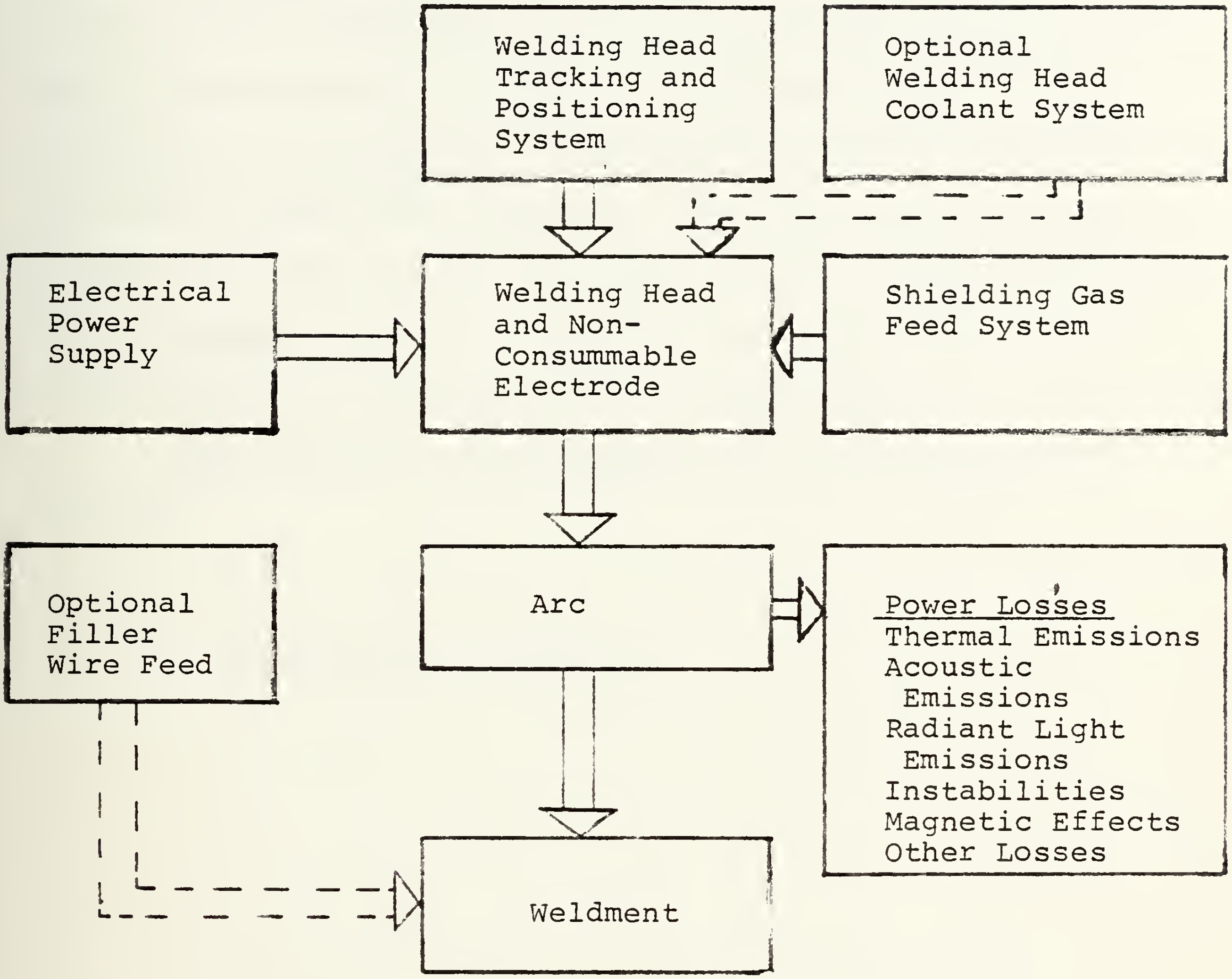


FIGURE 2-2

BLOCK DIAGRAM FOR MECHANIZED

GAS TUNGSTEN ARC WELDING SYSTEMS



To define a control scheme for these processes, first a brief discussion of nomenclature is required. Initially a simplified diagram will be proposed which will later be expanded into a final state variable model. The control vector $\underline{U}$ will be an m-component vector containing part or all of the above listed control variables. The state vector $\underline{X}$ will be defined as an n-component vector containing part or all of the above listed state variables. The final choice of the components of the control and state variable vectors should be the minimum set of variables that accurately describe all of the important functions of the welding process.

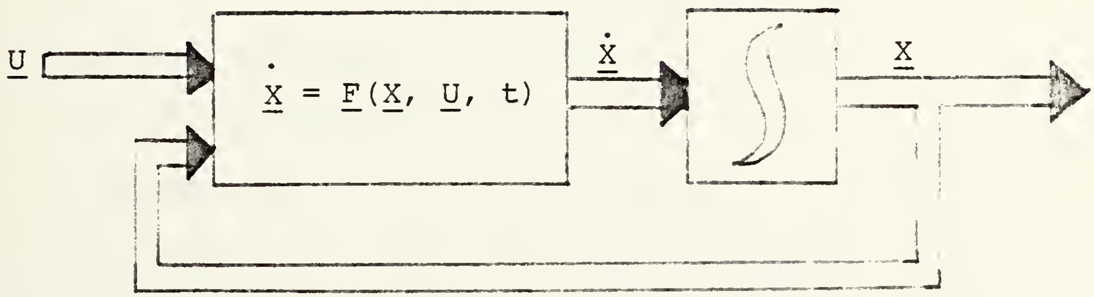
These vectors can be mathematically represented as follows:

$$\underline{U} = \text{vector of m control (manipulative) variables} = \begin{bmatrix} U_1 \\ U_2 \\ \cdot \\ \cdot \\ \cdot \\ \cdot \\ U_{m-1} \\ U_m \end{bmatrix}$$

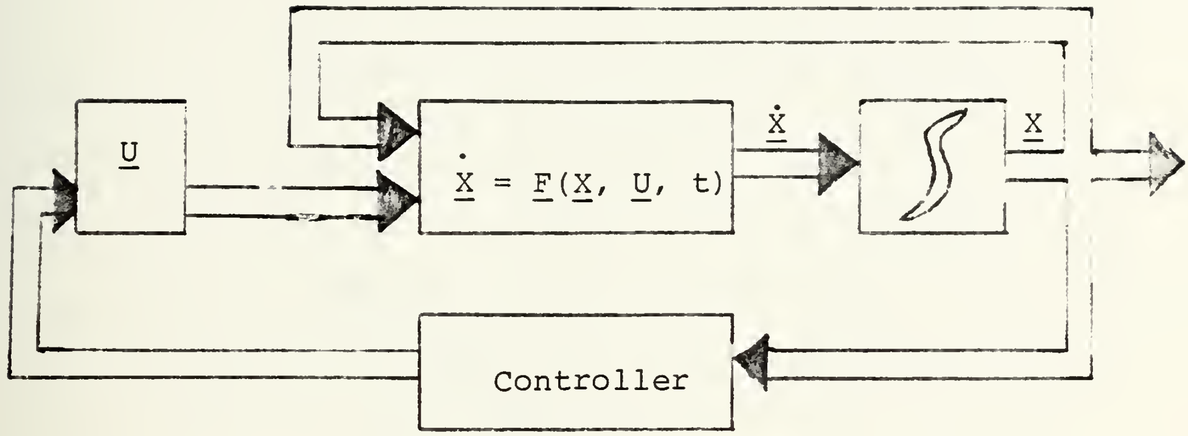
$$\underline{X} = \text{vector of n state variables} = \begin{bmatrix} X_1 \\ X_2 \\ \cdot \\ \cdot \\ \cdot \\ \cdot \\ X_{n-1} \\ X_n \end{bmatrix}$$

$$\dot{\underline{X}} = \frac{d}{dt}\,\underline{X}$$

Then the relationship between $\underline{X}$ and $\underline{U}$ can be diagrammed as



where $\underline{F}(\underline{X}, \underline{U}, t)$ is a set of time dependent, non-linear equations describing the welding process. By adding a controller to this representation, a closed loop process is obtained.



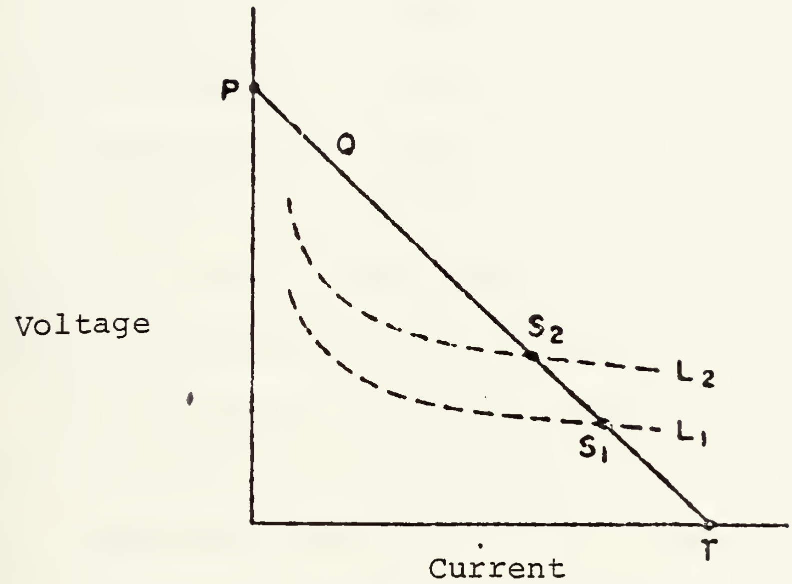
For the remainder of Section II, each control and state variable will be discussed in detail.

II.A. Control Variables

II.A.1. Arc Voltage and Current

The magnitude of voltage and current supplied by the power supply in the welding process is directly related to the amount of heat input that is supplied to the weldment once power losses are taken into consideration. Power supplies currently used in the GTA process have a "drooping" characteristic which supply a maximum open circuit voltage and then decrease to a zero value of short circuit voltage (Figure 2-3). Power supplies used in GMA processes have constant or increasing voltage characteristics (Figure 2-4).

FIGURE 2-3: Drooping Voltage Characteristics in Welding Power Supplies



DROOPING CHARACTERISTIC

L = arc length

$L_2 > L_1$

P = open circuit voltage

T = short circuit voltage

(Masubuchi, 18, p. 2-46)

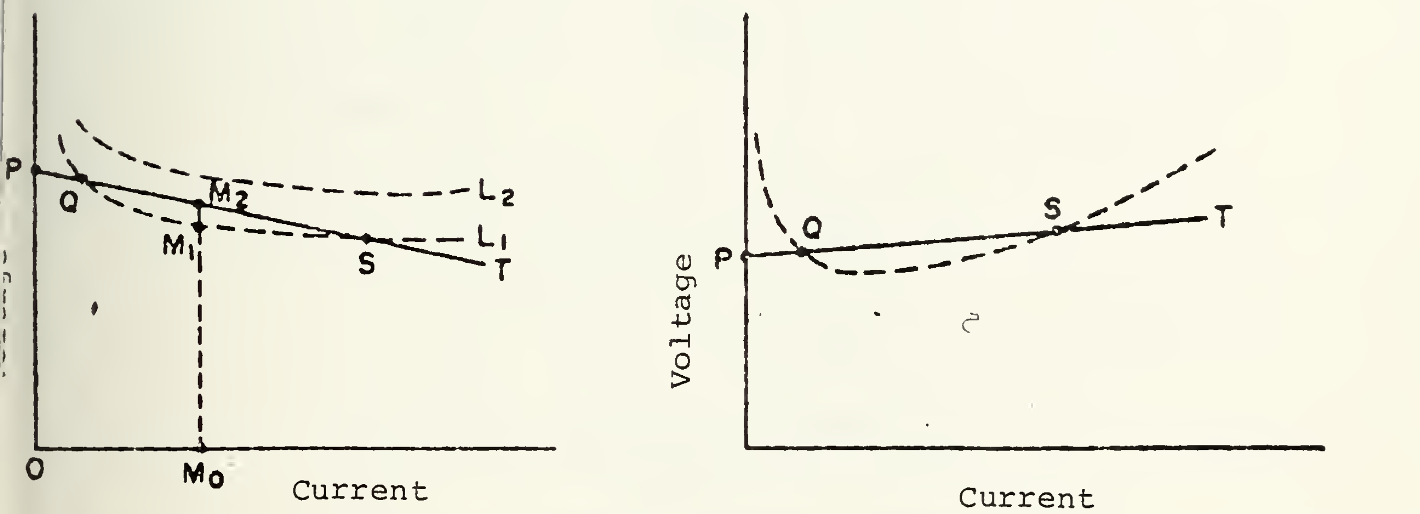
The constant voltage power supply allows the GMA process to self-regulate arc length because weld current, arc voltage and arc length are interrelated in the following way:

1. Arc length vairation in the GMA process is minimized if the melting rate (or burn-off rate) of the consummable electrode (inches per second) is equal to the feed rate of the electrode.
2. Arc length is directly proportional to arc voltage--increasing arc length increases arc voltage.
3. Melting rate increases with current increase.

For example, if the wire-feed speed increases, the arc length and arc voltage decreases, causing an increase in current. This increase in current increases the melting rate and burns-off the electrode more quickly; therefore the arc length increases (Masubuchi, 18, p. 2-49). Schaper, in reference 30, has discovered experimentally that welding performance in the GMA process is further improved if the power supply is capable of providing both the characteristics of constant voltage and constant current (Figure 2-5) by operating over the entire volt-ampere range; an example of such a machine is the TEK-TRAN linear slope control power supply type LSC 750.

For the majority of applications in both the GMA and GTA processes, direct current is used. Alternating current has limited, specific applications such as the

FIGURE 2-4: Constant-Voltage and Increasing Voltage Characteristics in Welding Power Supplies



a. CONSTANT-VOLTAGE CHARACTERISTIC b. INCREASING-VOLTAGE CHARACTERISTIC

L = arc length

$L_2 > L_1$

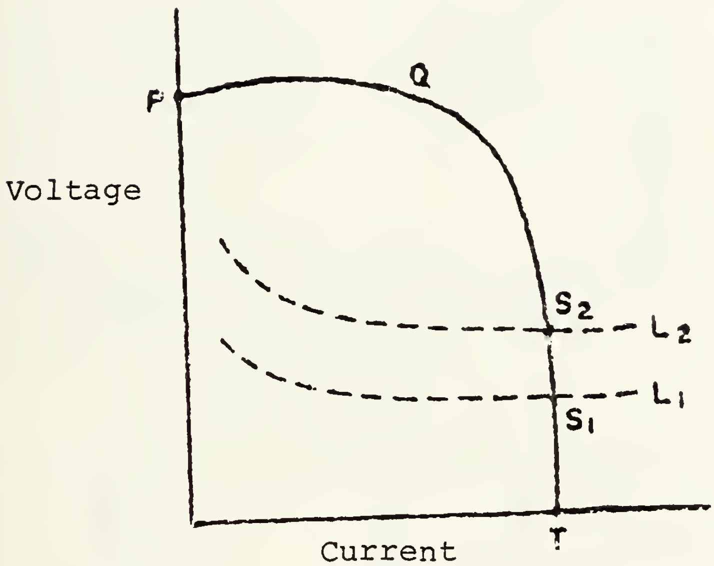
P = open circuit voltage

Q = unstable arc operating point

S = stable arc operating point

(Masubuchi, 18, p. 2-48)

FIGURE 2-5: Constant Current Characteristics in Welding Power Supplies



CONSTANT-CURRENT CHARACTERISTIC

L = arc length

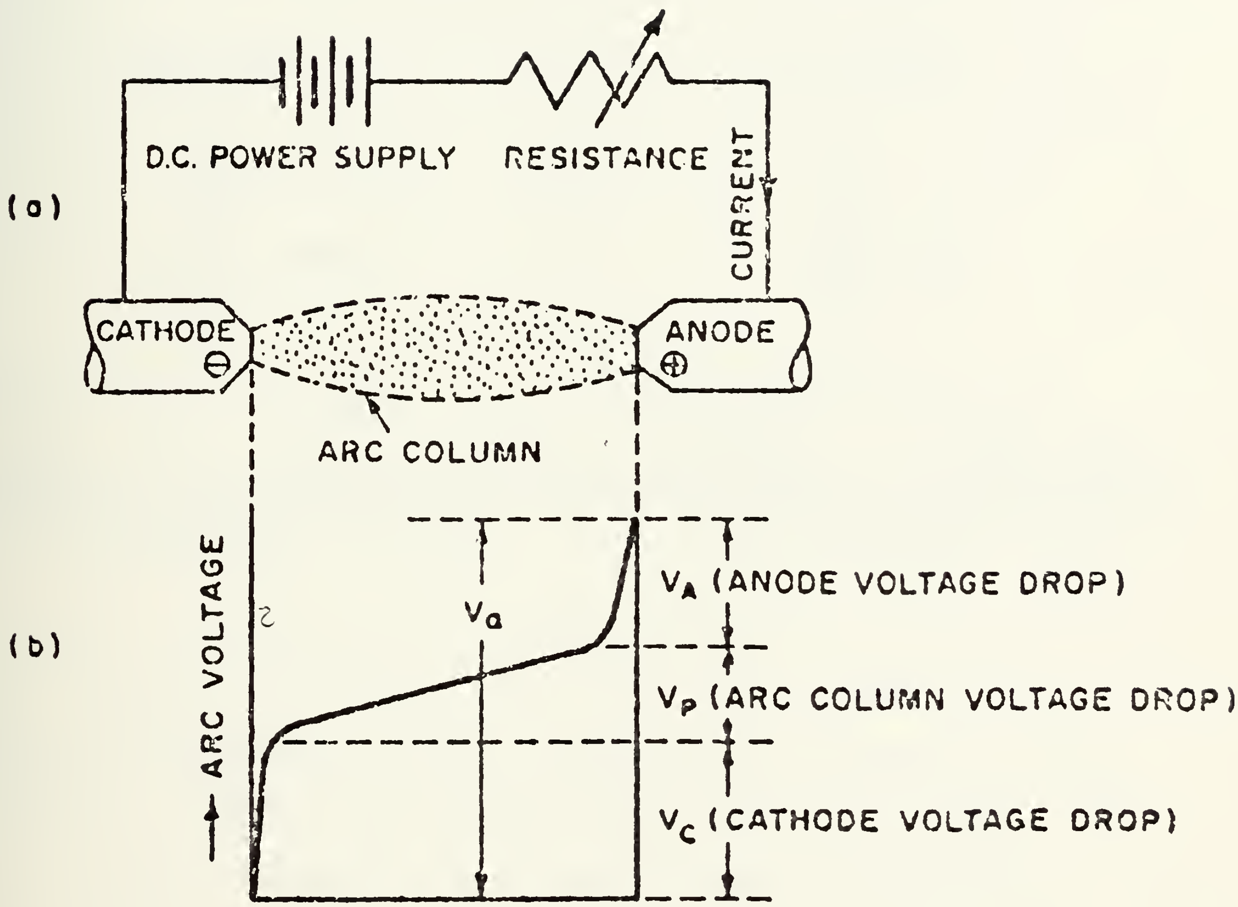
$L_2 > L_1$

P = open circuit voltage

T = short circuit voltage constant current value

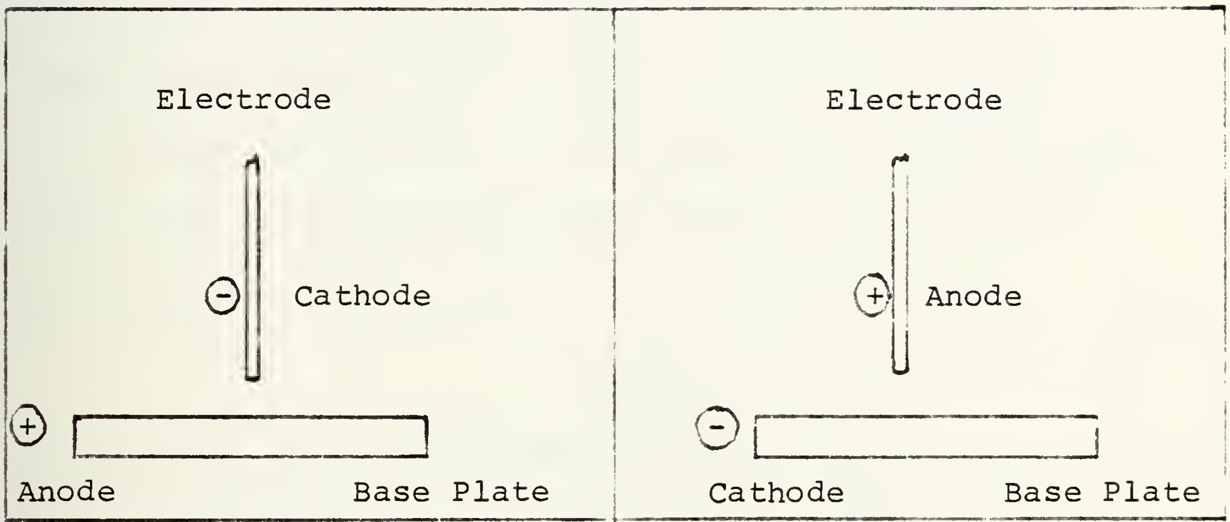
(Masubuchi, 18, p. 2-46)

FIGURE 2-5A: Voltage Characteristics of a Welding Arc



(Masubuchi, 18, p. 2-6)

application of high frequency in the GTA process to improve the arc stability. In direct current applications, two choices of polarity are available and are labeled Direct Current Straight Polarity (DCSP) and Direct Current Reverse Polarity (DCRP).



Direct Current Straight Polarity	Direct Current Reverse Polarity

DCSP is used in the majority of GTA welding applications because approximately 80% of the heat is developed at the Anode in a welding arc and 5% of the heat is developed at the Cathode. Primarily, the use of DCRP in GTA welding occurs when Aluminum or Magnesium are welded; the oxide coating on these metals is removed much more readily when using DCRP by an unknown mechanism (possibly the positive ions striking the plate) (Masubuchi, 18).

Conversely, DCRP is the most common polarity used in GMA welding. DCRP provides a faster melting rate of the electrode and, consequently, a higher metal transfer rate.

II.A.2. Shielding Gas

The primary consideration regarding the shielding gas is the correct choice of the right gas mixture; also, these gas mixtures must be free of impurities because any gas impurities can cause arc instabilities. These gas mixtures have been determined experimentally for different applications and are summarized in the table below:

TABLE 2-2

SHIELDING GAS APPLICATIONS

GTA			GMA		
Base Metal	Gas	Polarity	Base Metal	Gas	Polarity
Steels	Argon Helium	DCSP	Stainless Steel	Argon + 1% O_2	DCRP
Aluminum Magnesium	Argon Helium	DCRP	Carbon Steel	CO_2 or CO_2+O_2, Argon + O_2	DCRP
Titanium	Argon Helium	DCSP			
			Alloy Steel	Argon + O_2, CO_2, or CO_2+O_2	DCRP
			Quenched & Tempered Steel	Argon + CO_2	DCRP
			Aluminum	Argon Helium	DCRP
			Copper	Argon Helium	DCRP

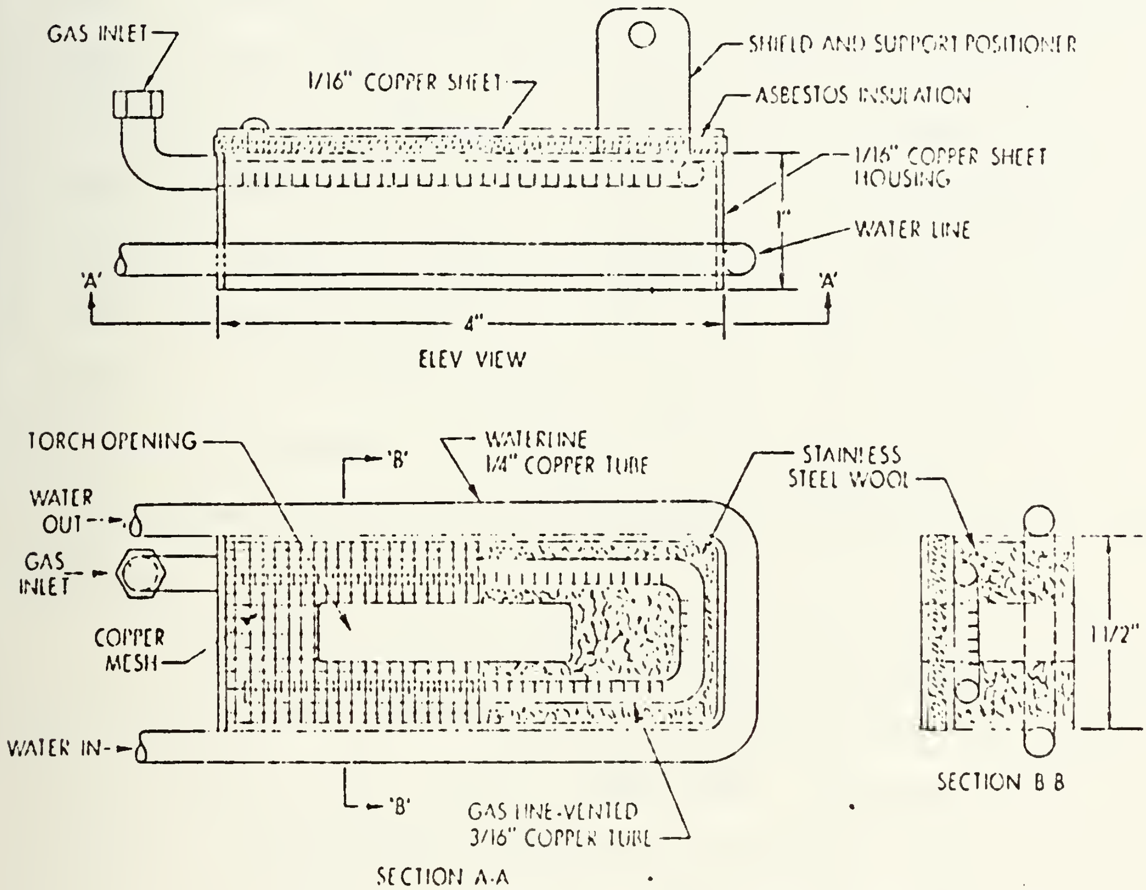
The purpose of the shielding gas is to provide a shield from atmospheric contamination which causes porosity, embrittlement, cracking, and other problems. Schaper (reference 30) has developed a gas shield configuration which has significantly increased the ability of the shielding gasses to exclude the atmosphere from the weldment. This new shield has proved capable of dispersing the gas thoroughly and is diagrammed in Figure 2-6.

Potential dynamic uses of the shielding gas have been discussed but not confirmed experimentally. For example, it may be possible to control the temperature on the outside arc boundary or even to position the arc by directing the flow of the gas. However, these dynamic uses may be invalid for outdoor applications on windy days even if they are developed.

II.A.3. Pulsing Shape and Frequency

Current pulsing has applications in both GTA (Troyer, 33) and GMA (Lesnewich, 17) welding processes; the effects of pulsing for welding control are substantial and to date have not been completely documented. For example, in the GTA process pulsing can be used advantageously to agitate the weldment puddle to improve fusion and prevent cracking. However, the desirability of pulsed current is best understood by examining its effect in GMA applications.

FIGURE 2-6: Gas Shield Configuration Developed at David W. Taylor Naval Research and Development Center



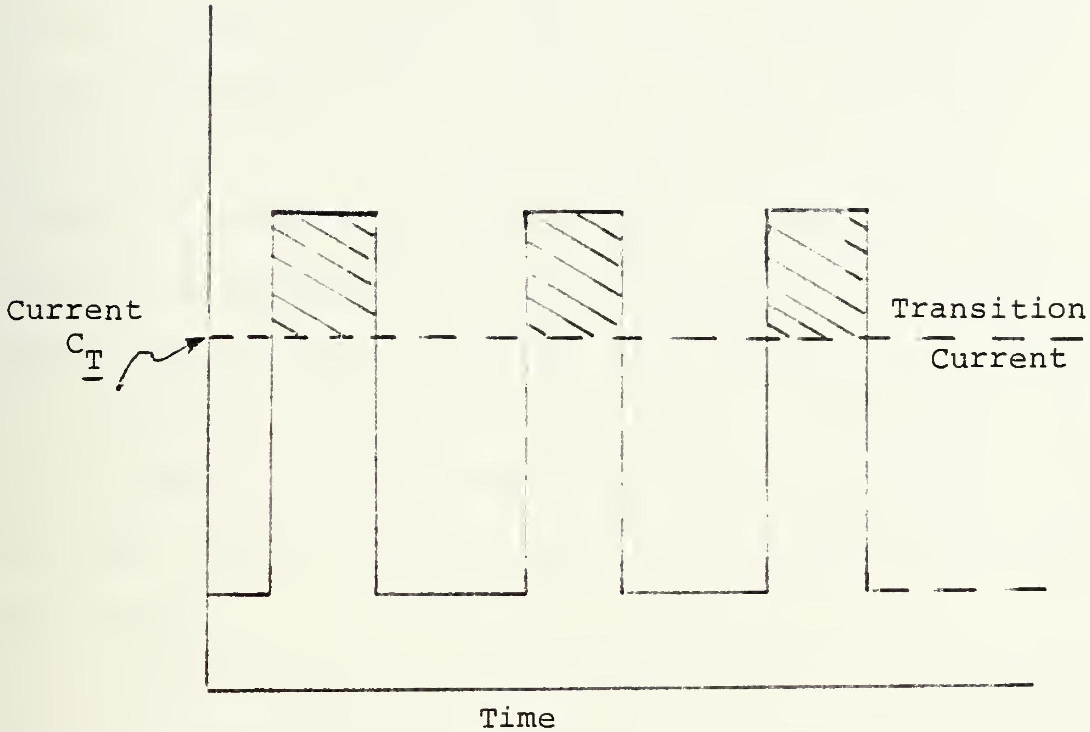
(Schaper, 30, p. 6)

The metal transfer mode in GMA is determined by the magnitude of the applied current. To achieve spray transfer (metal transfer modes will be discussed later), the magnitude of the current must reach a certain level. However, once this transition current value is reached, the metal transfer rate and the depth of penetration increase tremendously and are difficult to control. Therefore, to maintain an average low applied power and to control the metal transfer rate, current pulsing is used. Pulsed-power supplies provide a low average current but at the peak of the square wave pulse exceed the transition current (Figure 2-7). Consequently, the metal transfer rate and depth of penetration can be controlled by choosing the frequency and magnitude of the pulses.

Although pulsing is a promising variable with which to control both the GMA and GTA welding processes, much more developmental work must be completed. Currently, the magnitude and shape (square wave) of the pulses are pre-programmed into the machine. However, once a larger empirical data base is obtained, active frequency and pulse shape variations may be implemented as part of a closed loop control scheme.

FIGURE 2-7

CURRENT PULSING



(Lesnewich, 17, p.4)

II.A.4 Traverse Speed

Electrode traverse speed is inversely proportional to the amount of heat energy applied to the weldment. As the traverse speed decreases, the heat input increases. Most current machines implement a constant traverse speed. However, by measuring variables such as weldment puddle width and metal temperature distribution, traverse speed can be controlled and become a useful variable.

II.A.5. Electrode Tracking Path

To reduce joint preparation costs and to minimize joint allignment problems, some form of closed-loop tracking system should be incorporated as was discussed in the introduction of this study. Evans (reference 7) has performed a fairly extensive survey of electrode tracking systems in use through 1974. Generally, these systems are equipped with either mechanical or optical sensors which follow the joint. For example, the commercially available "Arc-Tender" described by Evans uses a mechanical probe that is inserted into the joint ahead of the torch and "feels" the path much like a blind person might use a cane.

Optical photocell sensors have also been incorporated which also have the added advantage of sensing and controlling arc length (Evans, 7, p. 18). However, the two most promising methods of sensing the joint path appear to be either a television (or video scan) camera or the Cecil mechanical cross-slide tracking and sensoring system.

The Cecil system has been used successfully in shipyards and has most recently been used by Schaper for a narrow gap welder that is being developed at the David W. Taylor Research and Development Center. The system consists of a transducer controlled finger probe which is placed about 1/4 inch ahead of the torch and senses irregularities

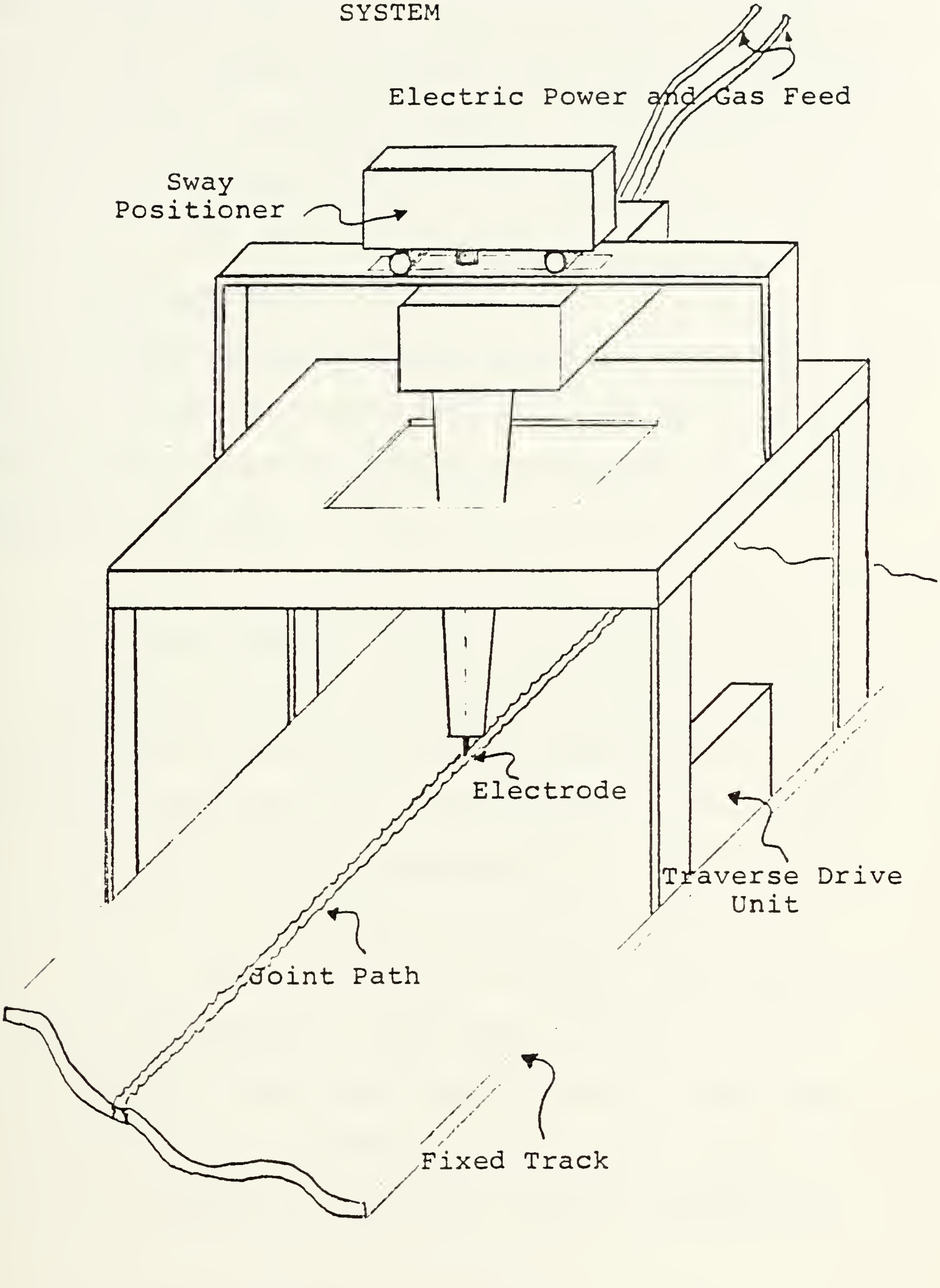
in the joint sidewall. It can operate in joint thicknesses from 0 to 2 inches (Schaper, 30, p. 6).

The television tracking system is attractive because it would not only provide joint path information but could also provide information regarding the weldment puddle width. In case of either the mechanical, transducer or television sensor, joint irregularities would be used to position the electrode via some form of servomotor drive. Probably the most useful configuration for the tracking system would involve mounting the torch on a carriage drive that follows a preset track; this track could be horizontally or vertically attached in the case of plate welding or could be circumferentially attached in the case of pipeline or cylindrical welding (Figure 2-8). The servomotor positioning drive could then have the capability of positioning the torch ±2 inches (or as much as required) from the centerline of the preset track.

II.A.6. Welding Torch Movement

The tracking system described above would give the torch two degrees of freedom. Additional degrees of freedom added to the torch would allow it to more closely duplicate the motions used in manual welding. Using the terms of Naval Architecture, the tracking system provides control of surge (electrode traverse speed) and sway

FIGURE 2-8: POSSIBLE HORIZONTAL ELECTRODE PATH POSITIONING SYSTEM



(servomotor positioning). Additional controls of heave (vertical), roll (angular rotation about the axis parallel to the joint path), and pitch (angular rotation about the axis parallel to the sway axis) may be useful.

II.A.7. Wire Feed Rate

In most GMA applications, wire feed rate is preset and invariant. However, wire feed rate could be made variable and would be useful for controlling arc length. Experiments are needed in this area.

II.A.8. External Magnetic Fields Surrounding the Arc

Jose Converti has suggested a form of magnetic arc control that he has begun to test experimentally using the GTA process (Converti, 13). By positioning 4 magnetic sensors at 90° intervals circumferentially about the arc, arc position and rate of change of arc position can be detected. Then, through the use of a set of deflection coils, the arc can be positioned in the joint. Possible other advantages of this scheme may be the control of arc shape and the control of arc instabilities. Dynamic control of the arc in this manner may have some useful consequences.

II.B. State Variables

II.B.1. Puddle Shape and Size (Penetration)

Vroman and Brandt (reference 34) have shown that the weldment puddle width can be measured using a video scan camera and this measurement can be used to control the torch traverse speed. The puddle width was preset into the controller and the welding process attempted to maintain this width throughout the length of the weldment. Good results were obtained from this experiment with the weldments displaying a high degree of uniformity.

Vroman and Brandt suggested that this puddle width information also be used to manipulate the welding current. Limitations on the use of this variable are based primarily upon the accuracy and resolution capability of the video scan camera. However, puddle width is a good indication of the amount of heat input to the weldment and the metal deposition rate.

II.B.2. Metal Temperature Distribution

By employing a temperature sensor such as a thermocouple at the front and back side of the weldment, indications about depth of penetration and heat input can be obtained. Bennett (reference 3) and Smith (reference 32) have indicated that this is a viable means of control. Some practical implementation considerations exist however;

for example, access restrictions to the back of the weldment are encourtered in pipeline welding or in the repair of large, high pressure steam lines. However, a NASA development in 1967 of a "hybird" thermocouple system for GTA aluminum welding proved that useful information could be obtained from the torch side of the joint only (Evans, 7, p.18). The hybird thermocouples consisting of a constantan wire which contacted the aluminum near the arc. Holding the voltage constant, either the torch travel speed or the current were varied to maintain a constant temperature. The following conclusions were made from this NASA project:

- Thermocouple insensitive to radiated arc interference and variations in surface emissivity.
- Surface oxides produced no interference.
- More successful for aluminum plate thicknesses of 1/8 inch or less.
- No observable lag in response time.

II.B.3. Arc Temperature, Arc Shape and Composition

Arc temperature can also be detected by some form of micro-thermistor or micro-pyrometer. However, many factors affect the arc and much more study regarding arc physics is required. For example, the principal arc temperature is determined by the choice of the type of shielding gas. The ionization potential for Helium (24.5 eV) is higher than the

ionization potential for Argon (15.7 eV); therefore the Helium arc temperature is significantly higher than the Argon arc temperature. The arc dynamics probably hold much useful information for the welding engineer but the physical mechanism is not fully understood at this time.

II.B.4. Arc Length

Arc length is a critical variable in the welding process and must be controlled precisely. As stated previously, arc length is proportional to arc voltage and may also be regulated by the wire feed rate. Other information regarding arc length may be contained in the arc temperature emissions, light emissions and acoustic emissions; the acoustic emission relationship will be discussed below.

II.B.5. Metal Transfer Mode (and Rate)

The metal transfer mode in the GMA process can take one of three forms: globular, spray (axial or rotating), or short-circuit (dip). The transfer mode is a complicated phenomenum and is a function of many factors such as:

- Shielding gas type
- Current (I)
- Polarity (DCRP, DCSP)
- Electrode diameter (d)
- Electrode extension or stick-out (L)

·Electrode metal type (steel, Al, etc.)

·Activation of the electrode with alkali, alkaline earth and rare earth materials (Masubuchi, 18)

The Globular mode (Figure 2-9) involves the transfer of large volume drops of metal (typically larger in diameter than the electrode) from the electrode to the weldment at the rate of 3 or 4 per second. These drops travel at a relatively low velocity. The Axial spray mode is the most desirable for most applications and consists of many small volume metal droplets that are accelerated to high velocities in a direction parallel to the length of the electrode. This mode deposits metal directly into weldment; it is the most efficient and stable mode. When the welding current exceeds a certain value, the electrode tip begins to rotate and sprays the metal at extremely high velocities in a cornical-type pattern. This rotating spray mode is highly unstable and should be avoided.

For certain applications, short-circuit or dip transfer is desirable. For example, dip transfer can be used to increase the depth of penetration when welding steel. In dip transfer, a large metal globe is formed on the end of the electrode which simultaneously contacts the weldment; this globe then separates from the electrode and is accelerated into the weldment (Figure 2-11).

FIGURE 2-9: Globular Transfer Mode

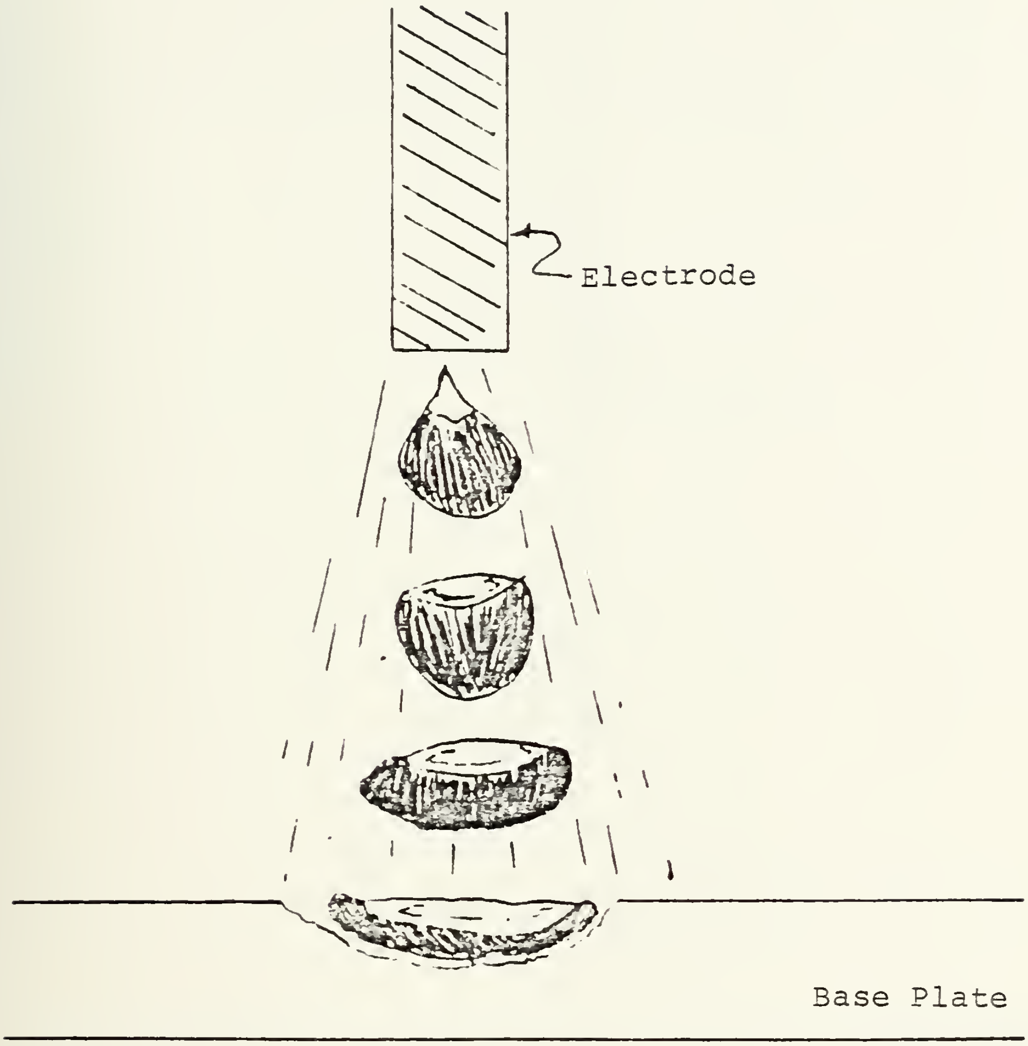


FIGURE 2-10: Axial Spray Transfer Mode

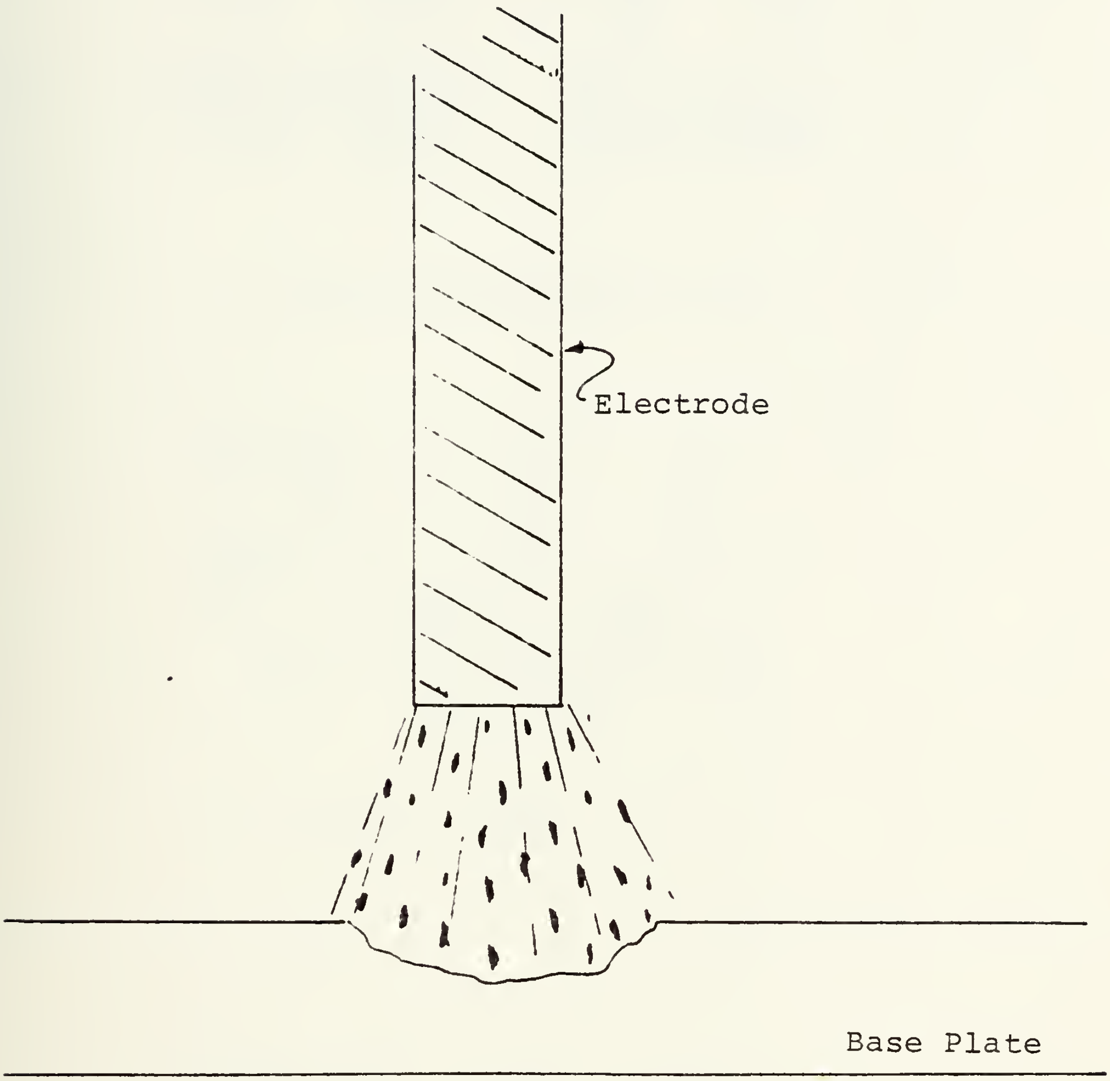
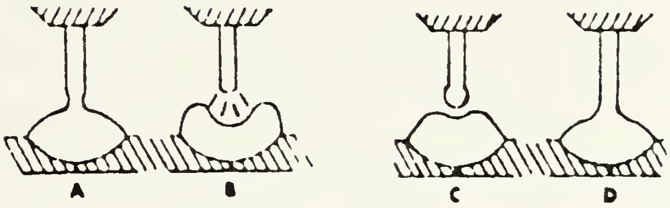
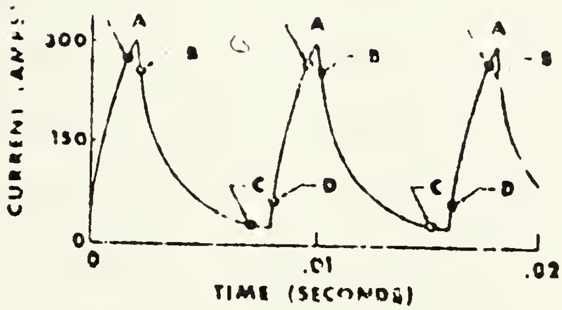


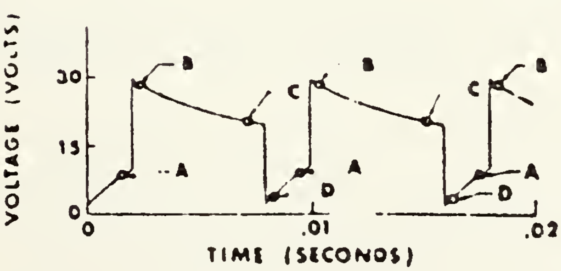
FIGURE 2-11: Short Circuit (or Dip) Transfer Mode



a. Change of Electrode Position



b. Current vs Time



c. Voltage vs Time

(Masubuchi, 18, p. 3-29)

The amelioration of the transfer mode from globular to axial spray occurs at a value of current known as the transition current. At this value of current, the drop volume decreases significantly and the drop velocity increases (Figure 2-12). The value of current required in the transition region varies with the electrode material, the electrode diameter and the electrode extension. The electrode extension length determines how much resistance heating occurs as the electric power is conducted through the electrode; as the length increases, the resistance increases and the resistance heating increases. As the conductivity of the material increases, extension length becomes less of a factor. From a qualitative viewpoint, the transition current magnitude decreases as extension length increases and increases as electrode diameter increases (see Figures 2-13, 2-14, and 2-15).

The metal transfer mode is a very critical variable in GMA welding and should be one of the primary considerations in any control scheme. Table 2-3 summarizes the important parameters affecting this variable.

II.B.6. Arc Magnetic Field

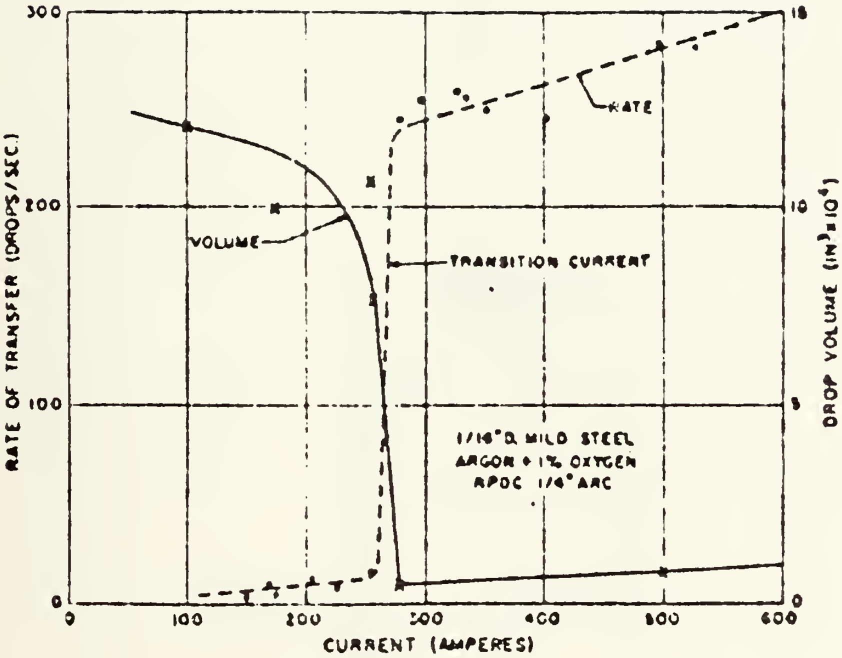
As discussed previously in the control variable section, the magnetic characteristics of the arc can be sensed and maybe used to deflect the arc. Other information may be obtained from this variable but extensive experiments must be completed first.

TABLE 2-3

FUNDAMENTAL MECHANISMS OF THE GMA METAL TRANSFER MODE

TYPE OF TRANSFER	MATERIAL	POLARITY	SHIELDING GAS
Globular		DCSP DCRP	Helium, Argon CO_2
Spray	Steel	DCRP DCSP with activated electrode	Argon only Argon
Dip	Steel	DCRP	CO_2

FIGURE 2-12: Transition Current in GMA Welding



(Masubuchi, 18, p. 3-17)

FIGURE 2-13: Shift in Transition Current Magnitude with Material

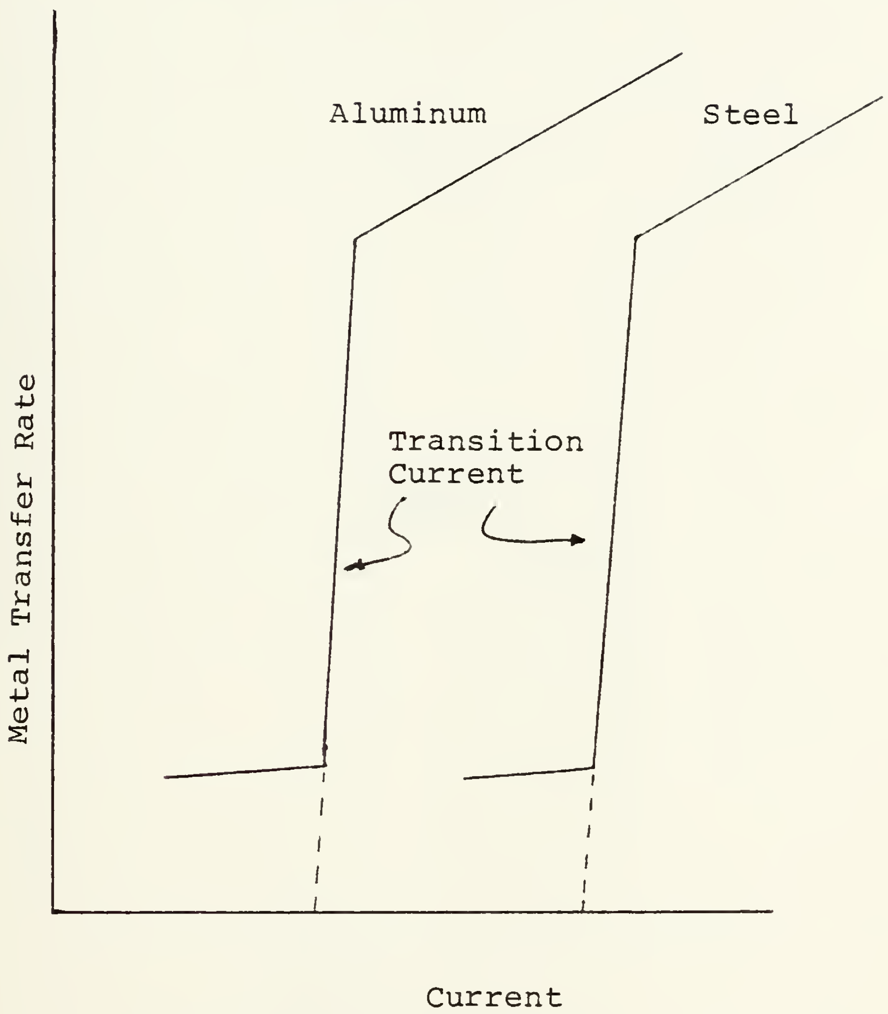
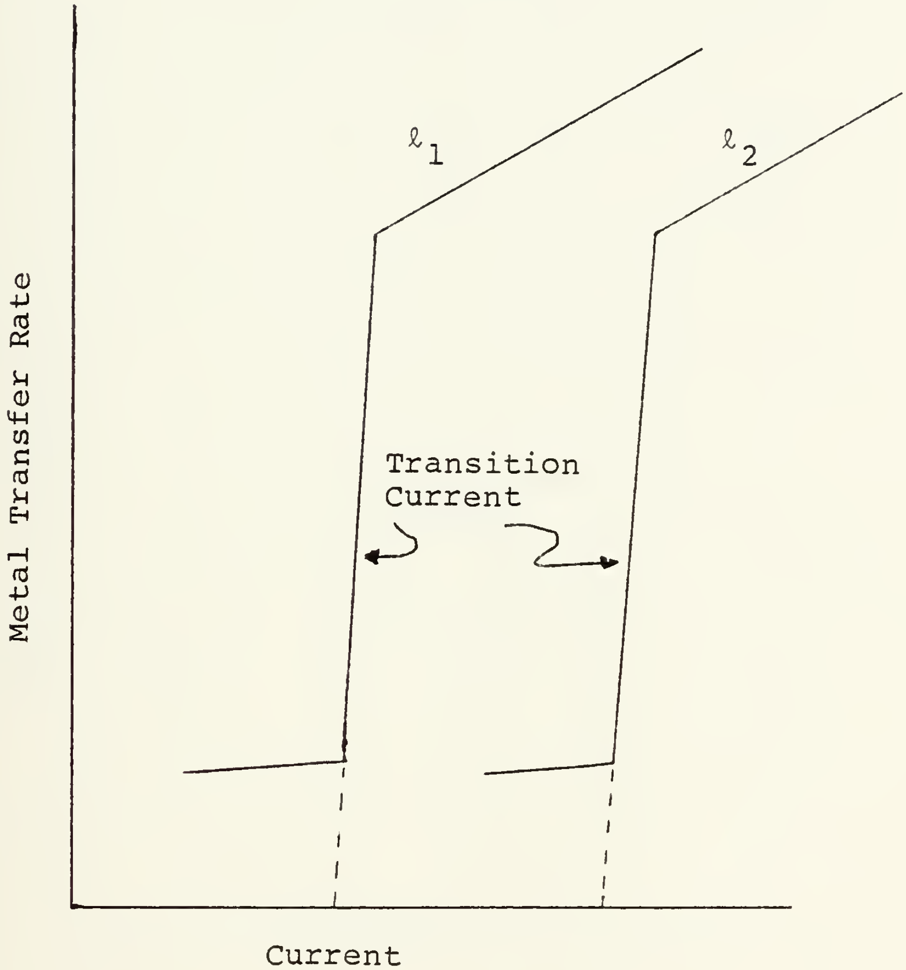


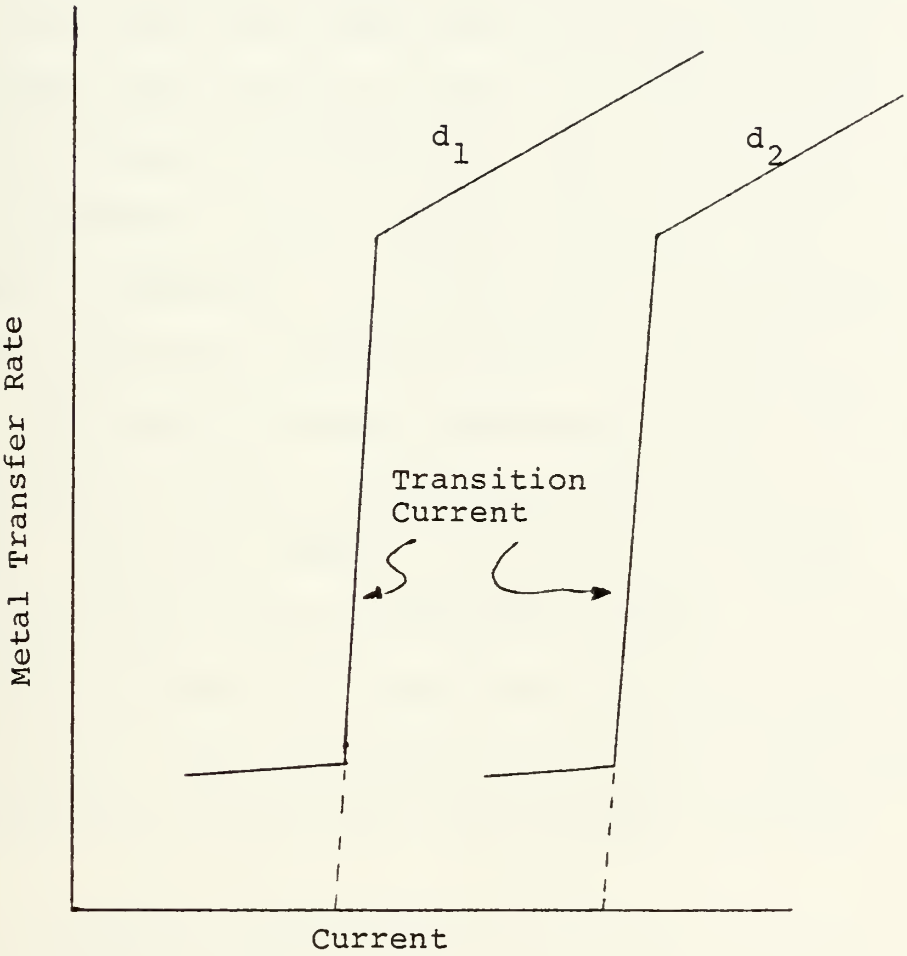
FIGURE 2-14: Shift in Transition Current Magnitude with Electrode Extension (Stick-out)



ℓ = electrode extension

$\ell_1 > \ell_2$

FIGURE 2-15: Shift in Transition Current Magnitude with Electrode Diameter



d = electrode diameter

$d_2 > d_1$

II.B.7. Radiant Light Emission

The light emission spectrum is one of the few variables listed in this section that is used as feedback by the manual welder. The brightness and intensity of the light is of sufficient magnitude that rapid damage occurs in the welder's eye unless protective shielding is worn. However, the ability of the welder to process anything other than "brightness" and arc length information from the light emissions is debatable. With the use of more sophisticated equipment, spectral information may be recoverable from the light. Experiments have been performed in this area and a patent titled "Control System Using Radiant-Energy Detection Scanning" (US Patent Number 3,370,151 of 20 February 1968) has been issued to Neil J. Normando (Vroman, 34, p. 749). Glickstein (reference 9) also lists two references pertaining to this topic. From the results of further experimental work, light emissions could prove to be a useful variable.

II.B.8. Acoustic Emissions

When observing a welding craftsman at work, one is amazed by what appears to be a lack of sensory feedback. Anyone who has attempted to initiate a shielded metal electrode arc while wearing the protective shield can appreciate the lack of visual feedback. However, the experienced welder still produces good welds.

Apparently, one of the feedback mechanisms that the welder uses is the crackling sound of a "good" weld. Welding shop foremen are able to monitor the progress of their production welders by listening to the sound; the sound has been described as the same sound bacon makes when frying in a pan.

In a short series of experiments conducted with Mr. Anthony J. Zona at the MIT Welding Lab, a correlation between the noise emissions and the arc length was observed. By assuming the noise emissions to be band limited white noise, the following figure (Figure 2-16) approximates the nature of the acoustic output during welding. These characteristics are based upon observations made during manual stick electrode welding of steel plate.

From these observations, the following conclusions were drawn:

- The central, or dominant, frequency (f_o) shifted to a lower value as the arc length increased.

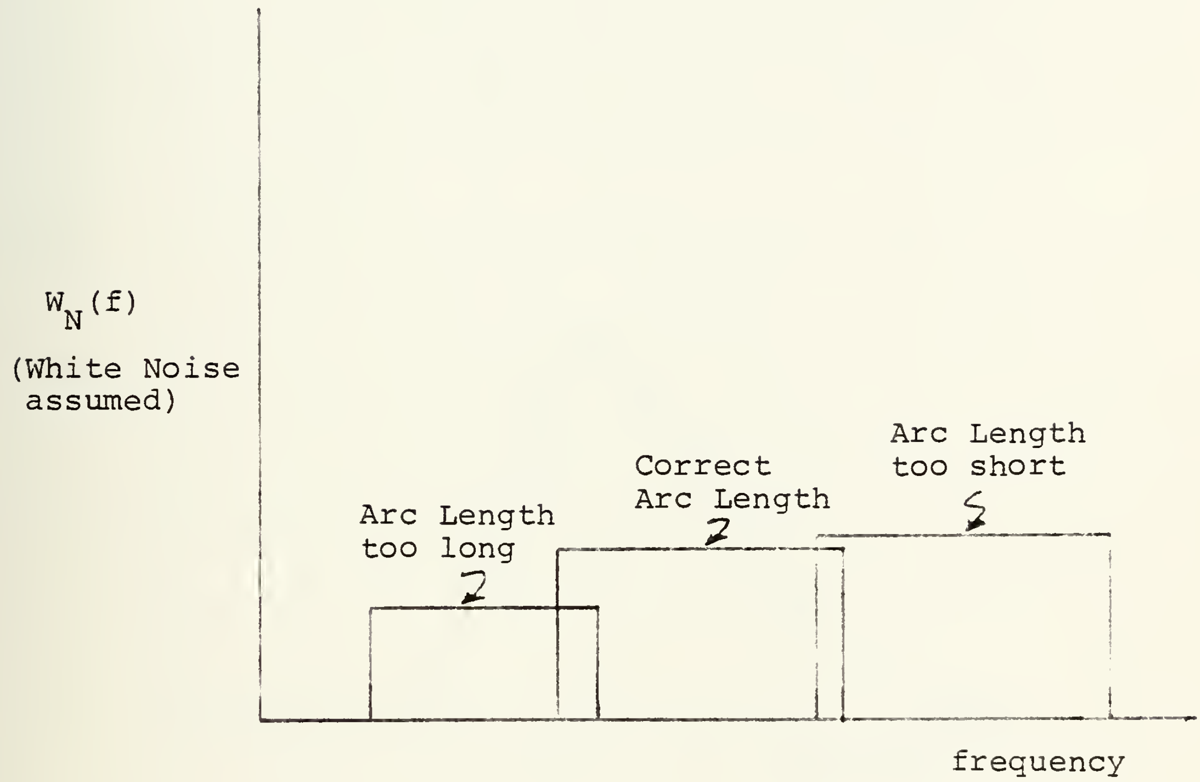
- As the arc length decreased, the frequency shifted to a higher value.

- Acoustic energy decreased as the arc length increased and increased slightly as the arc length decreased.

Although the acoustic energy is probably dependent upon many factors, metal transfer rate appears to be an important consideration.

FIGURE 2-16

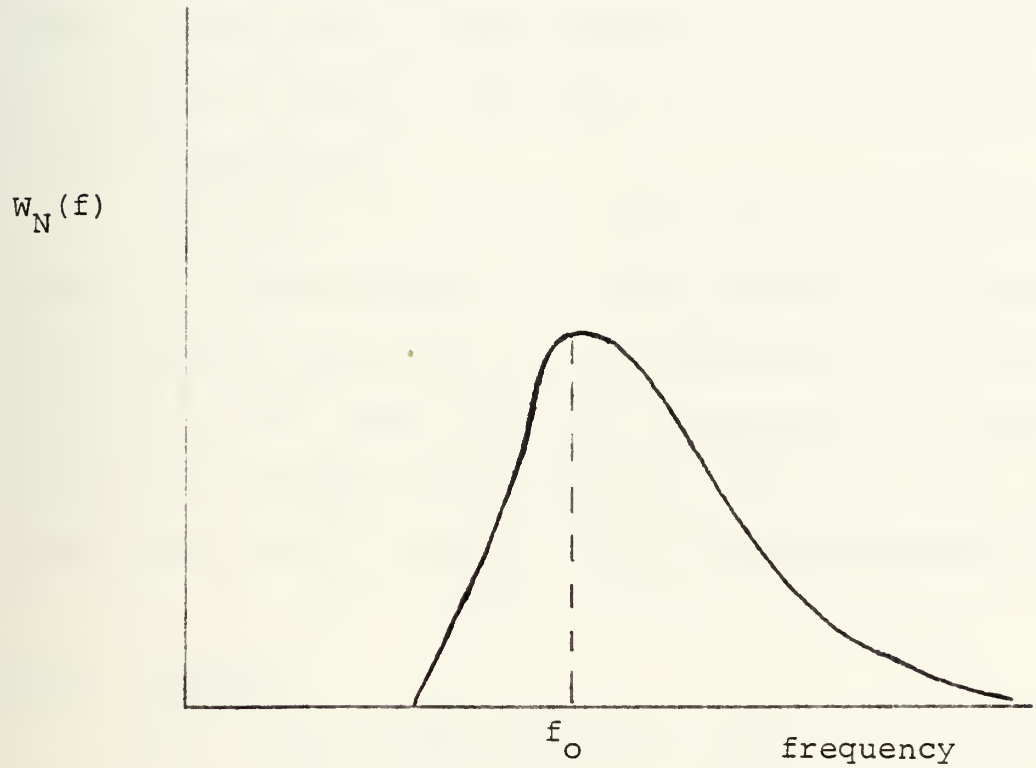
Noise Emission Characteristics in Manual Stick Electrode Welding



Actual spectral characteristics of the acoustic spectrum would have a more general shape; hopefully, the spectral density curve will have the appearance of Figure 2-17 Second order affects may be present in the form of peaks in the curve, but the curve as shown in Figure 2-17 has a dominant peak at f_o and then decays with frequency.

FIGURE 2-17

Possible Acoustic Emission Spectral Density



By attaching a directional transducer to the torch, these noise emissions could be measured and sent to a microprocessor. If the mean square value of the noise is the primary important parameter in these emissions, the signal could be processed quite easily. However, if the frequency distribution of the noise is important (observations indicate it is important), spectral density processing techniques would be required.

The instruments described in reference 1 have the capability of performing real time spectral density analysis over a band width of about five octaves. They have a sampling frequency of about 60,000 Hz and cost about $30,000 (1978 US) which may be fairly excessive for welding applications. However, if the noise is narrow banded about the peak frequency f_o, perhaps a cheaper instrument with a narrower band width could be fabricated.

If Figure 2-17 is the general appearance of the noise spectrum, optimal values of f_o would need to be obtained experimentally for each welding application. For example, according to Mr. Zona, the noise characteristics seem to change when welding in wet weather. This is a very complicated area and will require a lot of developmental work.

II.C. Summary

The variable descriptions in this section are designed to give the reader an appreciation for the complexity of the welding process; particular emphasis has been placed on the interactions that occur between the variables. Only through an understanding of this variable interaction can the control engineer begin to develop a model and a control scheme for welding. The references contained at the end of this work provide a more complete description of the fundamentals of welding; in particular, reference 18 discusses in-depth many of the variables that have been presented here.

Although an effort has been made to identify every potential welding variable that is important to an automatic welder, current knowledge limitations restrict the use of some of them in a model of the process. In the following section, an automatic welder model will be developed which encorporates ten of the variables listed in this section.

III. STATE VARIABLE MODEL

In this section, a state variable model will be developed to describe the GMA welding process. The GMA process is considered to have more applications in major ocean structural production and is therefore more important; however, a similar model could be envisioned for the GTA process.

III.A. Simplifying Assumptions

Because the total number of variables described in Section II is enormous, certain simplifying assumptions must be made to produce a meaningful model. These assumptions are based on one or both of the following:

- Lack of sufficient data or knowledge regarding the variable and its affect on the overall welding process.
- The procedure required to control the variable is well defined currently and this variable can be added to the model easily.

For the above reasons the following variables have been neglected from consideration in the final model:

- Electrode Tracking Path
- Welding Torch Movement
- Shielding Gas
- Pulsing Shape
- Noise Emissions

- External Magnetic Fields
- Arc Temperature
- Arc Shape and Composition
- Arc Magnetic Field
- Radiant Light Emission

The electrode tracking path can be controlled using existing technology and has no affect on the model once the assumption is made that the electrode remains in the joint. The major problem that will be encountered in controlling the movement along the joint path by the electrode is the choice of a suitable sensor that produces accurate and rapid position information.

Likewise, welding torch movement and manipulation can be implemented once the movement requirements have been defined. For the following model, the torch will have one degree of freedom--forward transversing or surge. Sway (sideways) motion is assumed but only in conjunction with the electrode remaining in the joint path.

For the remainder of the excluded variables listed above, not enough knowledge is currently available to determine the affect of implementing them in the control scheme. As further research is completed, these variables may be added to the model.

Finally, the model assumes that the type and diameter of the electrode have been chosen, that the shielding gas (Argon) has been chosen and that the material being welded has been chosen. Also, Direct Current Reverse Polarity is assumed.

III.B. Model Variables

The remaining variables are listed below along with a mathematical symbol which will be used in the model development. These variables are:

Control (or Manipulative) Variables

Variable	Symbol
·Current	I
·Voltage	V
·Traverse speed	v
·Pulsing frequency	ω_p
·Wire feed rate	C

State Variables

·Puddle (weldment) width	w
·Metal temperature	T_M
·Arc length	L_A
·Electrode Extension Length	L_E

These variables are assumed to be deterministic and measurable. Power supply characteristics are assumed to be known.

III.C. Model Formulation

Taking the variables as defined in Section III.B., the following vectors are identified.

$$\underline{U} = \text{Control (or Manipulative) Variable Vector} = \begin{bmatrix} I \\ V \\ v \\ \omega_p \\ C \end{bmatrix}$$

$$\underline{X} = \text{State Variable Vector} = \begin{bmatrix} w \\ T_M \\ L_A \\ L_E \end{bmatrix}$$

$$\underline{R} = \text{Reference vector (initial set points of the control vector)} = \begin{bmatrix} I_o \\ V_o \\ v_o \\ \omega_{po} \\ C_o \end{bmatrix}$$

$$\underline{Y} = \text{Output vector} = \begin{bmatrix} w \\ T_M \\ L_A \\ L_E \\ m \end{bmatrix}$$

The output vector contains the four components of the state vector plus m which is the metal transfer rate; m is defined as:

$$m = C_5(I, \omega_p, L_E) \tag{3.1}$$

Now by taking two equations proposed by Professor Masubuchi in his 13.17J course at MIT, the definition of the nature of the state relations can begin. These equations are as follows:

$$V = A_1 L_A + \frac{B_1}{d} I \, L_A + C_1 \tag{3.2}$$

(Masubuchi, 18, p.2-31)

$$M_r = A_2 I + B_2 L_E I^2 \tag{3.3}$$

(Masubuchi, 18, p.3-52)

A_1, B_1, C_1, A_2 and B_2 are constants. The symbol d is the electrode diameter and the symbol M_r is the melting rate. Then these relationships may be established:

$$\frac{d}{dt}(L_E) = \dot{L}_E = F_4(\text{melting rate}, \omega_p, C) \tag{3.4}$$

$$\frac{d}{dt}(L_A) = \dot{L}_A = F_3(\text{melting rate}, \omega_p, C, V) \tag{3.5}$$

$$\frac{d}{dt}(V) = \dot{V} = G_2(\dot{L}_A, L_A, I, \dot{I}, V_o) \tag{3.6}$$

Using the variable interaction descriptions contained in Section II, the remainder of the non-linear differential relations may be defined as follows:

$$\frac{d}{dt}(I) = \dot{I} = G_1(\omega_p, I, V, L_E, m, I_o) \tag{3.7}$$

$$\frac{d}{dt}(v) = \dot{v} = G_3(I, L_E, \omega_p, w, T_M, v_o) \tag{3.8}$$

$$\frac{d}{dt}(\omega_p) = \dot{\omega}_p = G_4(I, L_E, \omega_p, w, m, \omega_{po}) \tag{3.9}$$

$$\frac{d}{dt}(C) = \dot{C} = G_5(L_A, V, \dot{L}_A, \dot{V}, C_o) \tag{3.10}$$

$$\frac{d}{dt}(w) = \dot{w} = F_1(\text{Melting rate}, \omega_p, v) \tag{3.11}$$

$$\frac{d}{dt}(T_M) = \dot{T}_M = F_2(V, I, \omega_p, v) \tag{3.12}$$

By substituting L_E and I into the above equations for the melting rate and substituting for the derivative terms in the right hand side of the above relations, the final model equations can be listed below.

$$\dot{I} = G_1(\omega_p, I, V, L_E, m, I_o) \tag{3.13}$$

$$\dot{V} = G_2[F_3(I,L_E,\omega_p,C,V),L_A,I,G_1(\omega_p,I,V,L_E,m),V_o] \tag{3.14}$$

$$\dot{v} = G_3(I, L_E, \omega_p, w, T_M, v_o) \tag{3.15}$$

$$\dot{\omega}_p = G_4(I, L_E, \omega_p, w, m, \omega_{po}) \tag{3.16}$$

$$\dot{C} = G_5[L_A,V,F_3(I,L_E,\omega_p,C,V),G_2[F_3(I,L_E,\omega_p,C,V), L_A,I,G_1(\omega_p,I,V,L_E,m)],C_o] \tag{3.17}$$

$$\dot{w} = F_1(L_E, I, \omega_p, v) \tag{3.18}$$

$$\dot{T}_M = F_2(V,\ I,\ \omega_p,\ v) \tag{3.19}$$

$$\dot{L}_A = F_3(L_E,\ I,\ \omega_p,\ C,\ V) \tag{3.20}$$

$$\dot{L}_E = F_4(L_E,\ I,\ \omega_p,\ C) \tag{3.21}$$

The output vector becomes:

$$Y_1 = C_1(\underline{X}) = w \tag{3.22}$$

$$Y_2 = C_2(\underline{X}) = T_M \tag{3.23}$$

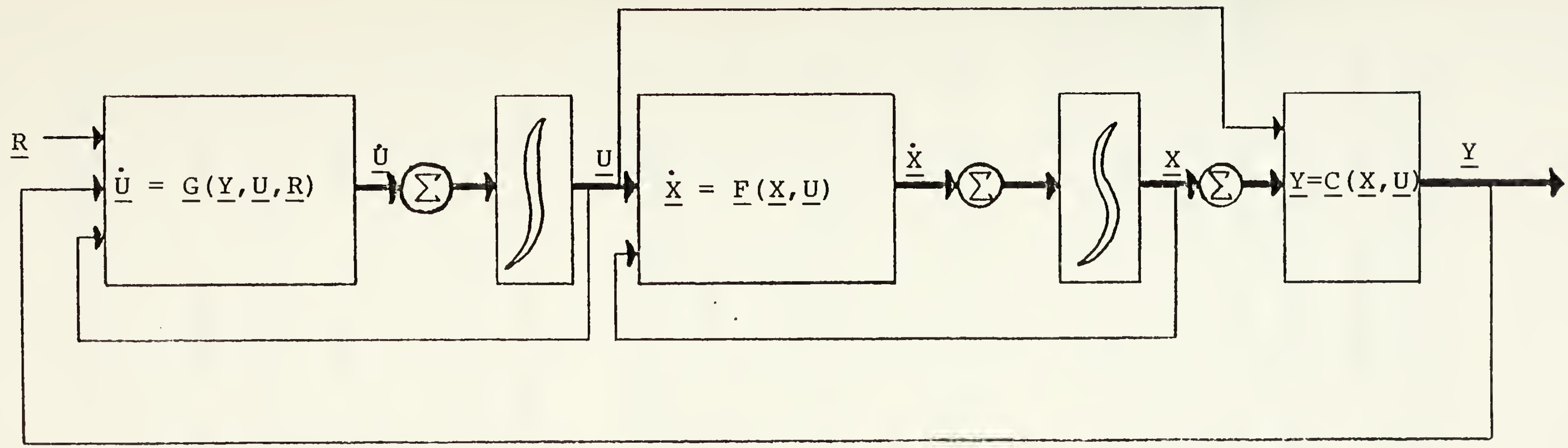
$$Y_3 = C_3(\underline{X}) = L_A \tag{3.24}$$

$$Y_4 = C_4(\underline{X}) = L_E \tag{3.25}$$

$$Y_5 = C_5(I,\ \omega_p,\ L_E) = m \tag{3.26}$$

The above relations define the ninth order model and the output. These relationships are diagramed finally in Figure 3-1.

FIGURE 3-1: State Variable Model for An Automatic GMA Welding Process



$$\underline{R} = \begin{bmatrix} I_o \\ V_o \\ v_o \\ \omega_{po} \\ C_o \end{bmatrix}$$

Reference

$$\underline{U} = \begin{bmatrix} I \\ V \\ v \\ \omega_p \\ C \end{bmatrix}$$

Control or

Manipulative

$$\underline{X} = \begin{bmatrix} w \\ T_M \\ L_A \\ L_E \end{bmatrix}$$

State

$$\underline{Y} = \begin{bmatrix} w \\ T_M \\ L_A \\ L_E \\ m \end{bmatrix}$$

Output

IV. RECOMMENDATIONS AND CONCLUSIONS

The model developed in the previous section is the first step in the implementation of an optimal control scheme for the GMA welding process. The following steps must be taken prior to the development, design and construction of an actual automatic welder using this model formulation:

- The nature of the vector functions $\underline{F}(\underline{X},\underline{U})$, $\underline{G}(\underline{Y},\underline{U},\underline{R})$ and $\underline{C}(\underline{X},\underline{U})$ must be determined.
- Power supply characteristics must be known exactly. Preferably, a power supply capable of operating anywhere on the V-I plane such as the one described by Schaper (reference 30) will be used.
- Sensors accurate enough to monitor the process variables must be developed.
- Values for the proper settings of the parameters in $\underline{R}$ must be determined for each application.
- Correct choices of parameters such as electrode diameter, electrode composition, joint alignment tolerance and shielding gas composition must be specified for each application.

The nature of some of the functional relations has been addressed in the literature but for the most part, only a few of the variables have been considered in the equation formulation. Little is known how such variables as pulsing frequency, metal temperature and weldment puddle width affect the exact form of the equation formulation. Secondly, even if the form of the equations does not vary with changes of metal being welding, electrode diameter, electrode composition and shielding gas, the constants and values of any exponents probably do. The first derivation for these equations should be accomplished considering steel plate welding in Argon gas shielding because this situation is the most prevalent for industrial needs.

The power supply characteristics will specify the operating regions available for the welding process; the power supply will be required to provide the current, voltage and pulsing characteristics as requested by the control scheme and is therefore the most important component in the process. Every effort should be made to make the power supply as adaptable as possible.

The settings of $\underline{R}$ have been researched extensively and are fairly well defined. $\underline{R}$ will vary with the choice of all parameters and will determine the operating set points of the process.

Likewise, parameter requirements have been fairly well defined in the literature for many GMA applications. These requirements are based on extensive empirical data.

Existing sensors have been discussed and, with the recent developments in electronic and video technology, should be available for welding control. These sensors should be able to provide sufficient accuracy.

Automatic control of the GMA process will entail a very complicated implementation procedure. Presented here has been a description of all identifiable process variables and a mathematical method of bookkeeping to define the variable interraction using modern control theory techniques.

In the following section, comments will be made regarding the implementation of this control scheme to welding. These comments are based on the authors's observations, research and experience and in some cases have not been documented by existing scientific evidence and fact.

V. COMMENTS REGARDING AUTOMATIC WELDING

The most important variable in the GMA welding process when using DCRP Polarity appears to be the current; both current magnitude and the frequency of the pulsing determine the majority of the physical mechanisms which occur. Current should be maintained so that the transition current is exceeded and axial spray transfer is maintained. Current and pulsing determine the melting rate of the electrode and affect the amount of heat energy that is applied to the weldment.

Therefore, the time rate of change of the current should be determined by measurements (and hence be a function) of most of the variables in the process. To do this, the power supply has to be adaptable enough to operate in the desired region. Schaper (reference 30) indicated that the quality of the weldments that he produced improved greatly once he shifted power supplies from a constant-voltage type to one that provided constant-current characteristics also.

If the current can be maintained in the region that insures axial spray transfer, the arc stability will increase and the mechanical properties of the weldment should be of good quality and should be reproducable.

Initial implementation of variable control for automatic welding will probably be completed on a model that is much simpler than the one given in Section III or on a model of the GTA process. The GTA process would be simpler to model because wire feed rate, melting rate and metal transfer rates can be ignored.

If the GMA process is chosen, one or two of the state variables (weldment puddle width and metal temperature) that are not easily measured can be deleted and then model development can proceed. Once computer model simulations have been completed, testing on actual welding machines would be advisable. After this first step is completed, other variables can be added to the model. Eventually one or two stochastic variables (light and noise emissions) should be added because they probably contain much useful information. These stochastic variables should unlock much of the mystery of the dynamic characteristic of the arc itself. Likewise, magnetic sensing and control of the arc will furnish more information about the arc mechanism.

Two different types of automatic welders are envisioned for the future. One type would be a large scale production machine that is controlled automatically in the joint path and is manipulated with little or no human intervention. This machine would probably be very large, very heavy, and

very expensive. However, another type of machine can be envisioned that could overcome the man-machine interface problem and use the manual skills as an integral part of the control scheme. This machine would be much smaller (maybe even portable) and less costly and would have uses such as repairs and on-site production.

Because manual manipulative skills and human sensor (eyes, ears, touch) capabilities are difficult to duplicate by machines, it seems tragic to eliminate them from welding. A human operator could ensure that the torch followed the joint path. The human operator could vary the traverse speed; even such a simple system as three "idiot" lights meaning "speed up," "slow down," and "OK" may be sufficient to control traverse speed. The machine could then manipulate other variables in the process. Welder training costs and training time would be reduced substantially while weldment quality would increase. As Houldcroft indicates in his article, the welder could be compared to the pilot in a commercial airline; the machine functions as an extension of the operator to greatly improve the overall system performance.

State variable controlled automatic welding has enormous potential to improve the fabrication capabilities of industry worldwide. As structural designs have become more complex and intricate, designers have demanded more efficient joining methods. The development of a variable controlled automatic welder should help to fulfill this need.

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c.1 Automatic welding control using a state variable model.